INTEGRATION OF INFORMATION IN SYNTHETIC VISION DISPLAYS: WHY, TO WHAT EXTENT AND HOW?

E. Theunissen, Delft University of Technology, Delft, The Netherlands
F.D. Roefs, Delft University of Technology, Delft, The Netherlands
R.M. Rademaker, Rockwell Collins, Cedar Rapids, Iowa
T.J. Etherington, Company Rockwell Collins, Cedar Rapids, Iowa

Abstract

Current experimental synthetic vision systems present a spatially integrated presentation of physical constraints such as terrain and obstacles. This paper presents a number of assumptions regarding anticipated procedures and the use of a synthetic vision system, and addresses the desirability of integrating temporary constraints related to the airspace, the airport and standard procedures. Following this, a number of examples are presented that illustrate a potential approach to integrate such information into a synthetic vision display. The paper ends with a discussion on the design of, and results from an experiment in which the influence of an integration of temporary constraint information on pilot decision making was examined.

Introduction

The rationale behind the use of synthetic vision display formats is to make the information regarding terrain and obstacles available to the pilot independent of visibility conditions [1]. The way information is made available influences the way in which the information is used. When using a data presentation concept in which a certain amount of the required information is integrated, there is a likelihood that the other, non-integrated information is overlooked.

The integrated depiction of flightpath, obstacle and terrain information in a synthetic vision display is intended to inform the pilot about the future flightpath and to provide sufficient awareness of the surrounding environment. Both in simulator and actual flight tests, a prototype of a synthetic vision display concept (Fig. 1) has been used to demonstrate that with respect to the guidance task, the display supports accurate manual control with low workload. With respect to the navigation task, the display provides a good awareness of the surrounding environment. In [2], the particular concept shown in Fig. 1, also referred to as a Synthetic Vision Information System (SVIS), is described in more detail.

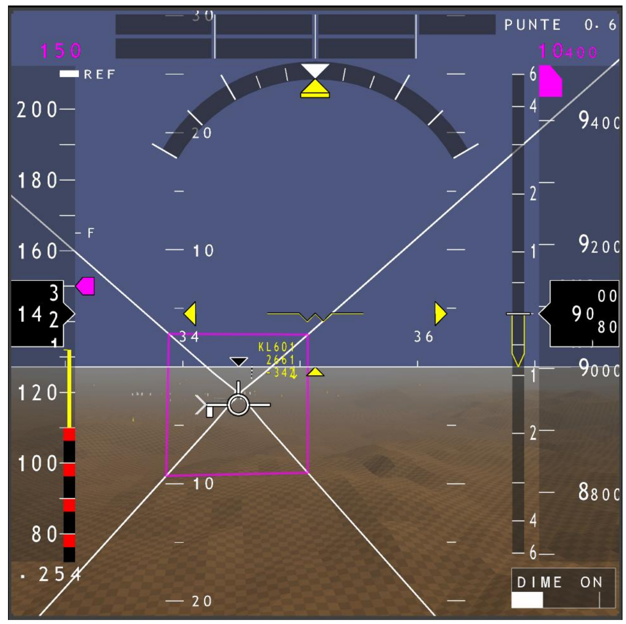

Figure 1. Example format integrating terrain, obstacle, flightpath, traffic and aircraft state information

Fig. 2 provides an overview of the data that is integrated in the display format shown in Fig. 1, classified by age of the data. Static data comprises terrain elevation data (e.g. from the Shuttle Radar Topography Mission), obstacle data (e.g. from the FAA), airport data (e.g. from the Safe Flight 21 survey [3]) and route data (e.g. from the FMS database). During the operation, both event-related data (e.g. ATC instructions) and real-time data are integrated. Based on the classification of the used data by its age, the following section addresses potential consequences when other data, imposing additional constraints on the situation, needs to be considered.

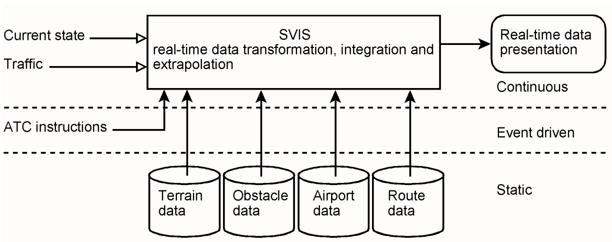

Figure 2. overview of the data that is integrated in the display format shown in Fig. 1

Why?

Potential issues

The underlying assumption for the use of the guidance display is that the depicted path assures a conflict free route. However, the update cycle of the FMS database from which the route is constructed, is typically three weeks. Temporary changes to a SID, STAR or MISAP within this cycle are published in a Notice to Airmen (NOTAM). The situation in which the pilot flies a path that according to a NOTAM is not to be flown should be prevented.

A category of constraints that is not integrated into the format depicted in Fig. 1 is the one comprising the temporary constraints for the airspace and the airport environment. Such constraints may have either a non-physical nature, e.g. restricted airspace or a physical nature, e.g. a taxiway closed due to maintenance. With current operations, the pilot is informed about these constraints by means of NOTAMs. This has raised the question regarding the desirability of visually integrating the temporal constraints into the presentation. This question will be answered through an analysis of potential situations in which the constraints may become relevant and a pilot-in-the-loop experiment.

When is the information needed?

During normal operations, the path guarantees a conflict free route, and the presentation of the terrain mainly serves to provide the pilot with a sufficient level of awareness regarding the surrounding terrain. This allows him to better take this information into account should the situation occur where he suddenly needs to deviate from the planned path.

In case the aircraft significantly deviates from the path, the pilot also needs to take into account any existing airspace restrictions. Besides for the separation with other traffic, he also relies on ATC to detect any potential (future) violation of restricted/prohibited airspace that may occur because of an error made by the pilot. Such an error may be caused by unawareness of the constraints or insufficiently accurate spatial awareness. Given the fact that terrain and obstacles are graphically represented in an ego–centered reference frame, whereas some of the airspace constraints are specified as text in a NOTAM, it is not unlikely that the accuracy of the location of the constraints in the pilots' mental spatial picture of the situation is less for these latter geospatial constraints.

Assuming that the situation of such a pilot error can occur, this raises the following questions:

- Given the potential consequences, is it sufficient to rely on ATC to timely vector the pilot away from the restricted or prohibited airspace?
- Are there operations during which it is desirable to ensure that the pilot has a more accurate awareness of the exact location of the constraints?

Given that ATC needs a certain amount of time to detect a potential airspace violation and vector the aircraft away from it, the need to ensure that the pilot has an accurate awareness of the location of restricted/prohibited airspace will increase with a decrease in temporal distance towards that airspace.

An example of an (experimental) operation during which an aircraft comes quite close to prohibited airspace is the river approach into runway 19 of Washington Reagan National airport (KDCA). Alaska Airlines has defined an LNAV/VNAV path that allows this approach to be flown using the FMS. During such an operation, the pilot is a supervisor. At several points during the approach, the aircraft comes within 3000 ft from the prohibited airspace P56A over Washington.

One cannot exclude the possibility that due to some unforeseen event, a certain part of the depicted route suddenly is no longer conflict free. Also, the automation may disconnect, requiring the pilot to take over manually. It is for these types of non-nominal situations that we think the concept of integrated presentation of airspace constraints has merit, both during a supervisory task and a manual control task.

Airport data

The database used to depict the airport layout is the result of a survey effort. Temporary changes to the airport such as closed taxiways and/or runways cannot always be timely provided through a database update. Similar to temporary changes in procedures, such constraints will be published in NOTAMs. This raises the question whether it is desirable to integrate this type of information in the surface guidance display(s). Under the assumption that the pilot is provided with a completely defined route from a specific runway exit to the desired gate, the information regarding closed taxiways and/or runways is not explicitly needed for the guidance task. If the pilot has a certain freedom in the choice of the runway exit, it is important that he/she is aware of closed exits.

The temporary layer

If the system should include the possibility to integrate information regarding temporary changes in procedures and temporary airspace and airport restrictions, an additional layer of information needs to be added. Fig. 3 shows how this layer fits in the overall structure of the SVIS depicted in Fig. 2.

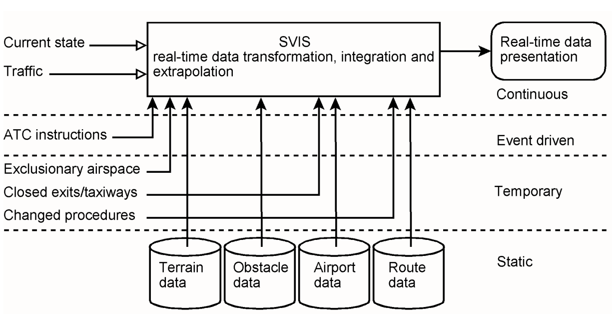

Figure 3. Addition of a layer of temporal information to the SVIS information structure

Uncertainty in physical constraints

It is unlikely that a terrain and obstacle database is completely error free. One approach that is being pursued to deal with this problem is the real-time integrity monitoring of the terrain database using measurements from the radar-altimeter [4]. The resulting system is also referred to as Database Integrity Monitoring Equipment (DIME). Integration with the display format would probably be in the form of a caution indication in case a mismatch is detected. Another approach to deal with situations in which either database errors or lack of information regarding other obstacles can reduce safety is the integration of real-time imaging data [5,6,7]. This latter option requires a closer integration with the SVIS illustrated in Fig. 3. Fig. 4 shows at which level this type of information is integrated into the proposed concept.

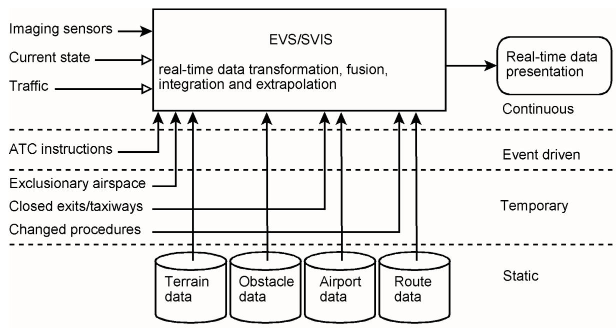

Figure 4. Addition of real-time imaging sensor data can be used to provide a hybrid synthetic/enhanced image to the pilot

When?

The discussion in the previous section has illustrated that in certain situations the quality of the pilot's decision is likely to be better when information about airspace and airport constraints is integrated in the SVIS.

Since the required level of awareness depends on the situation, this raises the question when the information about these constraints needs to be depicted. The following options exist:

- Always
- Pilot selectable
- Pilot selectable and automatic
- Automatic

Depending on the amount of data that is added to the display, the first option can be undesirable for those situations in which the likelihood of the information becoming relevant is very low and/or the temporal distance to the constraints is (still) high. For navigation on the airport, the data that needs to be integrated in the display to indicate closed taxiways and/or runways is minimal. During rollout, the temporal distance towards a closed exit can be so small that it makes sense to always integrate these constraints in the display. On the other hand, the indication of restricted airspace can require a considerable amount of display space even when conditions are nominal and the aircraft is still far away from any particular exclusionary airspace. This increases the potential for clutter. Therefore, the pilot should at least have the option to deselect the depiction of restricted airspace. To ensure that when the information becomes relevant for the decision making it is available on the display, rule-based logic needs to be defined that automatically enables the depiction of exclusionary airspace. The design question here is what the rules are that trigger the depiction. Two potential situations are when the actual navigation performance is worse than the required navigation performance and the occurrence of a TCAS traffic advisory.

How?

Fig. 3 showed the additional data layer that needs to be integrated. Fig. 5 shows how this can be performed for airport related NOTAMs. A similar approach is used for the airspace related restrictions, the difference being that these restrictions are not specified in an airport reference frame but by a set of latitude, longitude and altitude points or a latitude, longitude, altitude and a radius.

Depiction of airspace restrictions

Until now, the graphical representation of the constraint data has not been addressed. Similar to the spatially integrated presentation of physical constraints in the SVIS through the depiction of 3-D volumetric objects, the non-physical constraints such as exclusionary airspace can also be presented through a depiction of their boundaries.

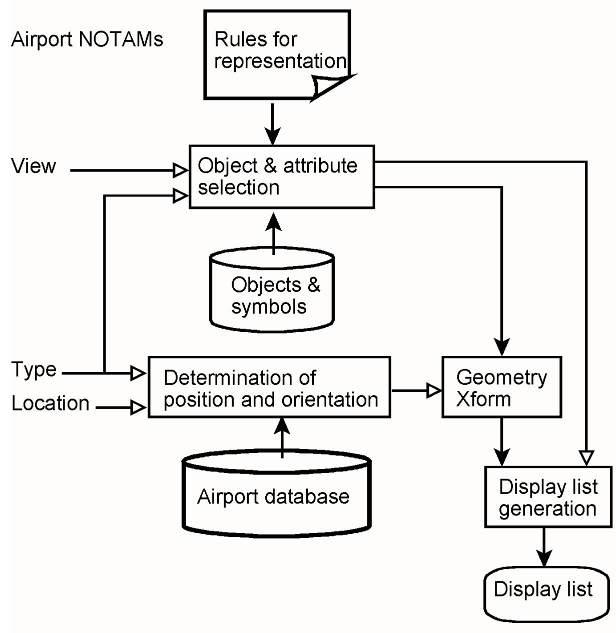

Figure 5. Integration of airport related NOTAMS concerning restrictions on runways and taxiways

This idea was already proposed in the context of the pictorial format program [8], in which volumetric objects in a perspective presentation of the aircraft environment represented areas of high lethality due to enemy SAM sites or AAA (Fig. 6).

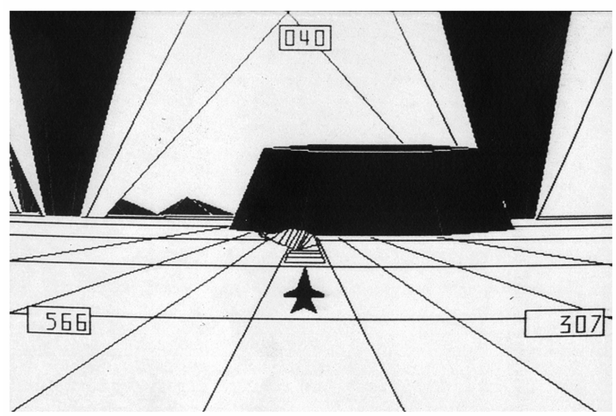

Figure 6. Depiction of airspace with a high lethality due to SAM or AAA [8]

Fig. 7 shows an example of how the airspace over Washington is depicted on the Primary Flgith Display (PFD) when flying the River approach into KDCA and Fig. 8 shows the Navigation Display (ND) with a footprint of the prohibited airspace.

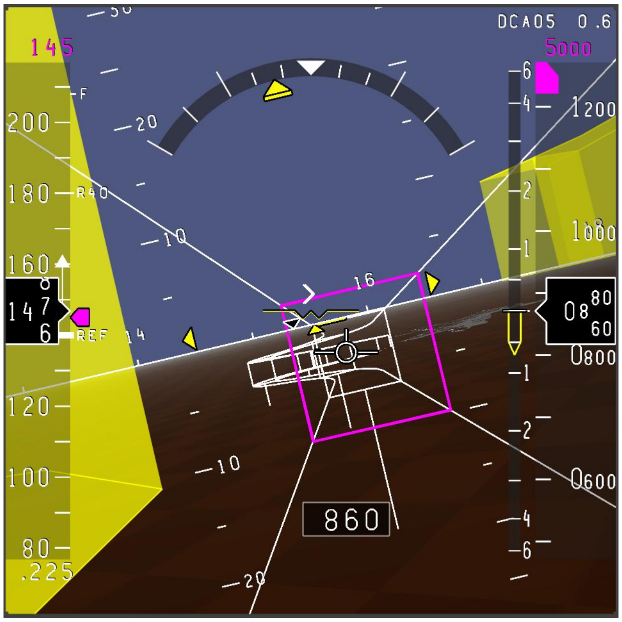

Figure 7. PFD during river approach to runway 19 of KDCA (July 2002)

Figure 8. ND for the situation depicted in Fig. 7

Depiction of airport restrictions

The depiction of airport restrictions is performed using a real-world analogy for the PFD and the usual X symbol for the ND. Fig. 9 shows the PFD with a closed exit, and Fig. 10 shows the ND for the same situation.

Figure 9. PFD with no-entry signs to indicate the closed Foxtrot exit

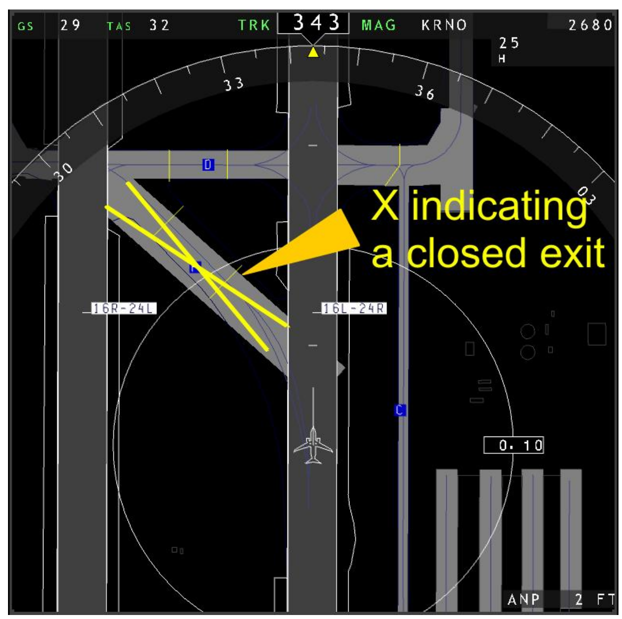

Figure 10. ND with a yellow cross to indicate a closed exit

Integration of imaging sensor data

The integration of imaging sensor data is an option to compensate for potential elevation and obstacle database errors and inaccuracies, and the detection of dynamic objects that are not provided by means of a datalink. Regal [5] discusses various options to fuse sensor data with a synthetic representation that were being considered for the Boeing high speed civil transport. In [6], an approach for the fusion of images with different spatial and temporal resolution is described, and in [7] the development of a synthetic vision system with a sensor inset is discussed. Fig. 11 presents an example of a sensor inset into the PFD format presented in Fig. 1. In the setup used to test the integration, the sensor image is integrated using a real-time capture of an RS-170 video signal from the sensor system. The ratio between the geometric field of view used for projection and the sensor field of view is used to compute the size of the inset, and the azimuth and elevation of the sensor relative to the aircraft body axis are used to compute the location of the inset. A filter is used to blend the edges of the sensor image into the synthetic scene. At present, a range of blending and filtering options are being investigated.

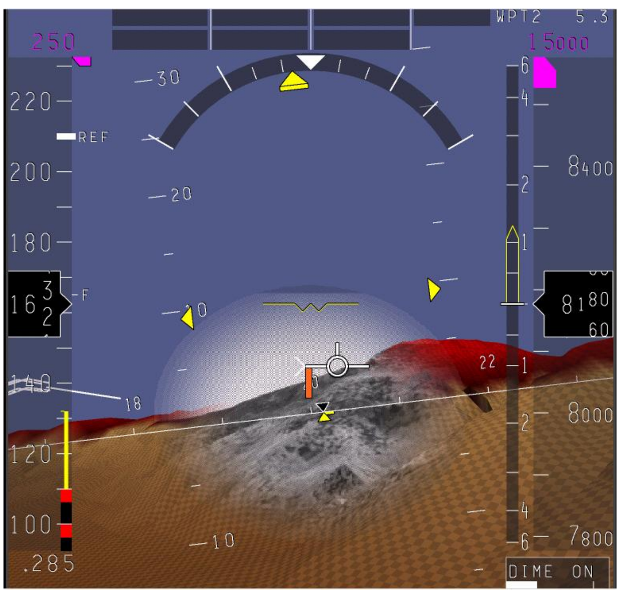

Figure 11. Example of integrated sensor information in the SVIS PFD

Evaluation

To obtain initial feedback from pilots regarding the need for integration of this type of information, an experiment has been conducted. The experiment did only address the influence on pilot decision making regarding the integration of NOTAM information about airspace and airport restrictions, and NOTAM information about changes to routes. Other data integration issues will be investigated in separate experiments. In the experiment that will be discussed next, pilots flew two different scenarios in a research flight simulator. Doing this, they were sometimes supported by the system with electronic NOTAM information (experimental condition; ‘E’), and sometimes by the system without electronic NOTAM information (baseline condition; ‘BL’). Also, before each trial participants read a paper NOTAM report, which they took with them in the cockpit of the simulator. Every participant flew both scenarios, one in the BL condition, one in the E condition.

In the experiment pilots flew approaches to Reno / Tahoe airport (Reno, Nevada). In both scenarios participants encountered a situation wherein they had to deviate from the predefined, conflict-free route. As mentioned in the introduction, in case of a deviation from the intended path it is necessary to be aware of all constraints that are relevant for that specific area, in order to be able to make the correct navigation decisions. The two scenarios were designed so, that it would be possible to deduct from the content, timing, and sequence of the decisions made by the pilots, whether they were showing reactive or anticipatory behavior.

Scenario 1

In Scenario 1 participants fly an approach to a specified runway. There is a restricted airspace in the area, mentioned in a NOTAM. After turning to final the participant first gets a TCAS TA, and then a TCAS RA to climb. At this time the aircraft is situated very close to the restricted airspace. The planned approach goes under the restricted airspace. By following the TCAS RA to climb, the participant will enter the restricted airspace. To the subject it is clearly impossible to avoid the restricted airspace by climbing over it, because the upper limit of the airspace is too high. The larger part of the restricted airspace is located to the left of the route. Therefore, the restricted airspace can best be avoided by diverting to the right. For this purpose, a diversion of approximately 10 degrees suffices.

In condition BL no electronic NOTAM information is shown on the SVIS. In condition E it is pilot-selectable whether or not electronic NOTAM information is shown on the PFD and/or the ND. However, once the aircraft leaves the tunnel, the NOTAM functionality is automatically turned on. In the case of scenario 1 this means that once the participant leaves the tunnel by climbing out of it after receiving the TCAS RA command to climb, both PFD and ND automatically show the restricted airspace.

Participants' performance is considered to be good when they show anticipatory behavior, and bad when they show reactive behavior. Performance was measured as follows: In case the participant contacts ATC either about entering the restricted airspace because of the TCAS RA, or about diverting to the right to avoid it, he shows anticipatory behavior (good performance). In case the participant does not realize that he will enter a restricted airspace by following the TCAS RA, he will climb out of the tunnel and into the restricted airspace. Because he is not aware of the restricted airspace, he will not contact ATC nor divert to the right to avoid it. In this case, the participant is contacted by ATC approximately one minute after entering the restricted airspace. ATC informs him that he has entered a restricted airspace, and vector him out of it. The participant shows reactive behavior (bad performance).

Scenario 2

In Scenario 2 participants fly a standard approach to Reno / Tahoe airport. During the approach they receive an ATC command that they have to land on runway 34L. They then have to select the standard procedure for this runway on the CDU, so that a final approach tunnel and the standard MISAP (missed approach procedure) for this runway are loaded. This MISAP however, has been changed as per NOTAM, the new MISAP being an existing departure route. At 250 ft. above the runway threshold, the participant is notified that there is a runway incursion, forcing him to fly a missed approach.

In condition BL the standard MISAP tunnel for runway 34L is shown. This is not the correct MISAP, the participant should fly the MISAP as described in the NOTAM. In condition E, the NOTAM text informing the pilot of the changed MISAP is displayed on the ND at the moment the runway incursion occurs. The electronic NOTAM causes the standard (and in this case faulty) MISAP tunnel not to be presented on either the PFD or the ND.

Participants' performance is considered to be good, when they fly the correct, changed MISAP (indicating anticipatory behavior). When a participant flies the faulty, standard MISAP, ATC contacts him. ATC then informs the participant of the fact that he is flying an invalid MISAP and vectors him to the correct MISAP. In this case, the participant shows reactive behavior, and his performance is considered to be bad.

Results

For each scenario the results are summarized in a table. Table 1 presents quantitative as well as qualitative results for scenario 1. For every participant Table 1 presents:

1. Did the participant notify ATC of either violating the restricted airspace, or changing heading in order to avoid it?

2. Did the participant avoid the restricted airspace or violate it?

3. How did the participant rate his awareness of relevant NOTAMs at critical moments?

4. How did the participant rate his ability to judge actual aircraft clearance with respect to restrictions?

The answers to questions 3 and 4 consist of ratings on a 5-point scale. The scores can be interpreted as follows: 1 = very poor, 2 = poor, 3 = neutral, 4 = good, 5 = very good.

Table 2 summarizes the results for scenario 2. For every participant Table 2 presents:

1. Did the participant fly the correct (changed) MISAP?

2. How did the participant rate his awareness of relevant NOTAMs at critical moments?

The answers to question 2 consist of ratings on a 5-point scale. The scores can be interpreted as follows: 1 = very poor, 2 = poor, 3 = neutral, 4 = good, 5 = very good.

Table 1. Summary of result for scenario 1

condition BL				
subject	**1 (notify ATC?)**	**2 (avoid / violate)**	**3**	**4**
1	no	Violate	2	2
3	no	Violate	3	2
6	yes	Violate	2	2
8	no	Violate	3	3
mean	n/a	n/a	2.5	2.3
condition E				
2	yes	Avoid	4	4
4	yes	Avoid	5	5
5	yes	Violate	5	5
7	yes	Avoid	5	4
mean	n/a	n/a	4.8	4.5

Table 2. Summary of result for scenario 2

condition BL		
subject	**1 (correct MISAP?)**	**2**
1	yes	4
3	yes	2
6	no	1
8	yes	3
mean	n/a	2.5
condition E		
2	yes	4
4	yes	4.5
5	Yes	4
7	Yes	4
Mean	n/a	4.1

Discussion

According to the rating criteria defined for the experiment, in both scenarios, all participants performed well in condition E (with electronic NOTAMs). In condition BL (without electronic NOTAMs), only one out of four participants performed well in scenario 1, and three out of four participants performed well in scenario 2.

So, overall performance was better in condition E than in condition BL. Furthermore, the scores filled in on the questionnaire indicate that participants rate their awareness and performance higher in condition E than in condition BL. Finally, from the answers to other questions on the questionnaire it was found that participants thought that workload was lower in condition E, and that they think electronic NOTAM information would be a very desirable feature.

The experiment also revealed a potential problem. Whereas for the rating, a lateral deviation was regarded as an indication of sufficient spatial awareness, in terms of procedures it can be regarded as not correct. Pilots need to follow the vertical TCAS command and not do any lateral maneuvering. They first need to contact ATC. In the debrief, pilots commented that they would like to be able to distinguish between the different types of exclusionary airspace, since this would influence their decision on whether to fly into it and contact ATC or avoid it using a lateral maneuver, even if that is not the right procedure.

Summary and Conclusions

This paper has discussed the addition of an additional layer of information to a synthetic vision information system that integrates information about temporary spatial constraints. The layer contains information about additional constraints that the pilot may need to take into account during non-nominal situations. At present this information is conveyed using charts and NOTAMs.

Both qualitative and quantitative data from initial pilot-in-the-loop evaluations indicate that the graphical integration of the additional constraint information increases the pilot's awareness of these constraints and reduces the likelihood of errors. Pilot comments indicate that the proposed integration is a desirable feature.

A way to allow the pilot to easily distinguish between different types of exclusionary airspace needs to be addressed, since situations may occur in which the pilot has to make the least bad decision.

References

[1] Williams, D., M. Waller, J. Koelling, D. Burdette, T. Doyle, W. Capron, J. Barry and R. Gifford. (2001). Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems Version 1.0.

[2] Theunissen, E., R.M. Rademaker and T.J. Etherington. (2001). 'Synthetic Vision - The Display Concept of the Collins Team', Proceedings of the 20th Digital Avionics Systems Conference, pp. 2C2.1-2C2.8, October 14-18, Daytona Beach, Florida.

[3] Safe Flight 21 Master Plan Version 2, Safe Flight 21 Steering Group, April 2000.

[4] Uijt de Haag, M., S.D. Young and R. Gray. (2000). DTED Integrity Monitoring Using Differential GPS and Radar Altimeter. Proceedings of the IAIN World Congress in association with the U.S. ION Annual Meeting, pp. 820-830, 26-28 June 2000, San Diego, CA.

[5] Regal, D. (1991). Synthetic Vision in the Boeing High Speed Civil Transport, Proceedings of the Sixth International Symposium on Aviation Psychology, pp. 198-203.

[6] Pavel, M., J. Larimer and A. Ahumada (1991). Sensor Fusion for Synthetic Vision. AIAA-91-3730-CP, pp. 164-173.

[7] Kruk, R., N. Lin, L. Reid, and S. Jennings. (1999). 'Enhanced/Synthetic Vision Systems for Search and Rescue Operations', Paper 1999-01-5659, Proceedings of the 1999 World Aviation Conference, October 19-21, San Francisco, CA.

[8] Way, T.C., M.E. Hornsby, J.D. Gilmour, R.E. Edwards and R.E. Hobbs (1984). Pictorial Format Display Evaluation. AFWAL-TR-84-3036, Wright Patterson AFB.

Abbreviations and Acronyms

AAA	Anti Aircraft Artillery
ATC	Air Traffic Control
CDU	Control Display Unit
DIME	Database Integrity Monitoring Equipment
FAA	Federal Aviation Administration
FMS	Flight Management System
LNAV	Lateral Navigation
MISAP	Missed Approach Procedure
ND	Navigation Display
NOTAM	Notice to Airmen
PFD	Primary Flight Display
RA	Resolution Advisory
SAM	Surface to Air Missile
SID	Standard Instrument Departure
STAR	Standard Arrival Route
SVIS	Synthetic Vision Information System
TCAS	Traffic-alert and Collision Avoidance System
VNAV	Vertical Navigation